TECHNISCHE UNIVERSITÄT CHEMNITZ

Estimation of Gait Parameters Using Joint Angles

Master's Research Project

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Abstract

Human gait is an important metric related to a person's health and well-being. Abnormal gait detection can be important for the diagnosis of neurological diseases. A disorder like dementia is a complex condition that affects millions of people especially those who are in their old age. The study of gait can be advantageous to diagnose dementia in elderly people in early stages. Also, gait analysis plays an important role in person identification and sports rehabilitation. This project aims to calculate the gait parameters of a person using the 3D pose data which is estimated using the RGB images and depth data captured by Kinect sensor. The 3D pose data gives the 3D coordinates of 25 joints of a person including knee, ankle, hip center, and so on. Knee flexion angle is used to plot the gait cycle of a given person using the 3D coordinates of hip, knee, and ankle joints. Using the gait cycle, we can calculate the stride time, stride length, step length, cadence, speed. In a similar way pelvic tilt is calculated using hip, hip center, and neck joints. The pelvic tilt angles are plotted against frame numbers and, stance and swing phases are identified. The calculated parameters are verified by comparing the parameters provided by a state-of-the-art system: Optogait.

Keywords: Gait Cycle, Gait Parameters, Knee Flexion Angle, Pelvic Tilt, 3D coordinates

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List of Abbreviations

RGB Red Green Blue
2D 2-Dimensional
3D 3-Dimensional
GA Gait Analysis
IR Infra-Red
OA Knee Osteoarthritis
CMOS Complementary Metal Oxide Semiconductor
FPA Foot Progression Angle

1 Introduction

Increasing in the elderly population is one of the main concerns of our society, as the balance between the elderly and working population will not be met in the near future. According to European Statistical Office the ratio between elderly and working people will be passed from 1:4 to 2:1, by 2060 in the EU. This situation can be improved by technological innovation and development to provide support through assistive and autonomous care services, which are based on cost-effective infrastructure that can be installed at homes or clinics[1].

Human gait is an important metric related to a person's health and well-being. The quality of gait not only depends upon on the physical strength of the person but also on the mental coordination process. For the same reason, abnormal gait detection can be important for the diagnosis of neurological diseases[2]. Neurodegenerative disorders like dementia is a complex health condition that affects millions of people and needs extreme care[3][4]. Studies suggest that dementia, age and gait deviations are deeply related[5][6]. Also, research proves that gait abnormalities can be seen in people with dementia due to defects of posture and equilibrium. So, the study of gait can be advantageous to aid the elderly people[3].

Human gait is complex and generally, a healthy adult performs it automatically. Elderly people require more attention to motor control than younger adults[7]. Falls and age-related health problems can be reasons for gait abnormalities. In elderly people performing other tasks while walking can cause disturbance to gait and in the worst case can result in a fall[3]. Such gait disorders detection allows timely intervention and potentially identify health conditions like dementia[8]. Gait Analysis(GA) is also used to assess the stage of Alzheimer's and Parkinson's diseases and to determine the recovery[9].

In addition to medical diagnosis gait also provides reliable means for identity verification. Automated Person Identification system is essential in the surveillance. Identifying a person through appearance, clothing, or objects carried by him/her, is unreliable. Gait analysis based on the skeleton is a successful approach in this aspect because it has no dependency on the appearance of a person. The stride length, the distance between joints, joint angles, speed, and acceleration, calculated from the 3D skeleton can be used for person identification[10].

GA has lots of applications that cover multiple aspects, including sports medicine and rehabilitation. GA along with biomechanical sensors is used to assess and correct the gait and also the posture of an athlete or an injured person[9]. Knee osteoarthritis(OA) is a common condition in the elderly which may need surgical intervention on severity. Gait measures are used to detect the recovery from knee replacement surgery[11].

This project aims to calculate the gait parameters of a person using the 3D pose data which is estimated using the RGB images and depth data captured by Kinect Sensor. RGB Data and corresponding depth data is acquired previously from elderly people using Kinect. The 3D pose data(skeleton) extracted gives the 3D coordinates of 25 joints of a person including knee, ankle, hip center, and so on. Knee flexion angle is used to plot the gait cycle of a given person using the 3D co-ordinates of hip, knee and ankle joints. Initially, vectors are formed between the hip and knee, knee and ankle. The angle between these two vectors gives the knee angle, which is used to calculate the knee flexion angle further. This knee flexion angles of all frames are plotted against the frame numbers to get the gait cycle which is of a standard curve for humans. The start of the gait cycle is the frame where the person's heel touches the ground initially. The gait cycle ends where the person's heel touches again.

Using the gait cycle, we can calculate the stride time, stride length, step length, cadence, speed. In similar way, pelvic tilt is calculated using hip, hip center, and neck joints. The pelvic tilt angles are plotted against frame numbers and stance and swing phases are identified. The calculated parameters are verified by comparing the parameters provided by Optogait. It is an industry standard used to calculate gait parameters in real-time. The calculated gait parameters, knee flexion angle, pelvic tilt are further analyzed using machine learning techniques to detect any abnormalities.

2 Background

2.1 Gait Terminology

2.1.1 Gait Cycle

Human walking consists of a consecutive periodic and harmonious movements produced by a sequence of collective actions, one leg alternating another. Although the movement of other body limbs can be selected, the gait cycle is normally defined as beginning with initial contact of the foot(Heel strike) and ending with the next contact of the same foot again, while the subject is walking as shown in figure 2.1.

Each gait cycle starts with the stance phase and proceeds through a swing phase until the cycle ends[12]. The stance phase is defined as the period in which the foot is touching the ground while the swing phase is defined as the period in which the foot is in the air before the foot strikes the ground again. The transition from the stance phase to the swing phase happens at the point when the subject's toe leaves the ground(Toe-Off) as seen in figure 2.1.

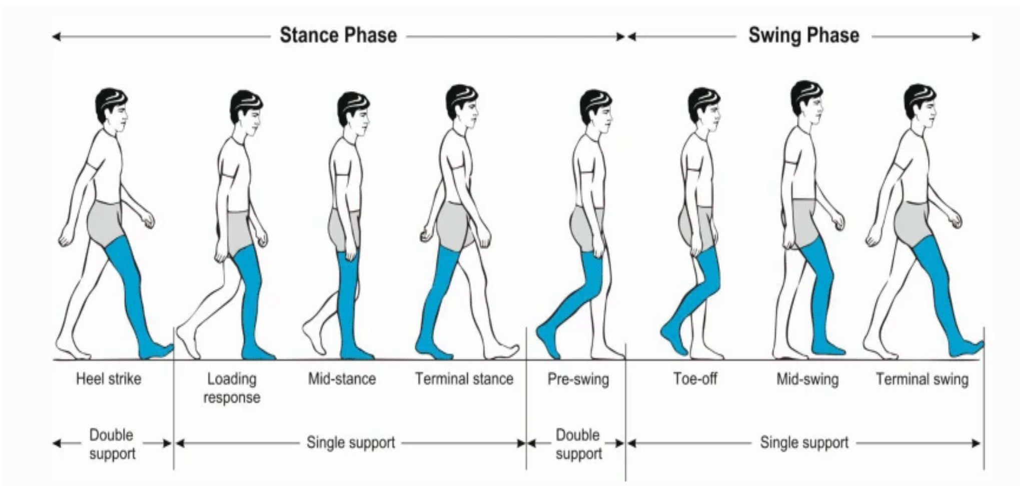


Figure 2.1: Phases of the gait cycle[13]

The stance phase and swing phase approximately covers 62% and 38% of the gait cycles approximately[14]. These percentages changes for each person and can be precisely calculated by knowing the time at which toe is leaving the ground. We can also distinguish between Single-support and Double-support based on the number of feet on the ground. The period during which both the feet are touching the ground it is called as Double-support and when only one foot is touching the ground it is called Single-support. There are two Double-support periods during walking whereas when running both feet won't touch the ground at the same instance of time.

2.1.2 Gait Parameters

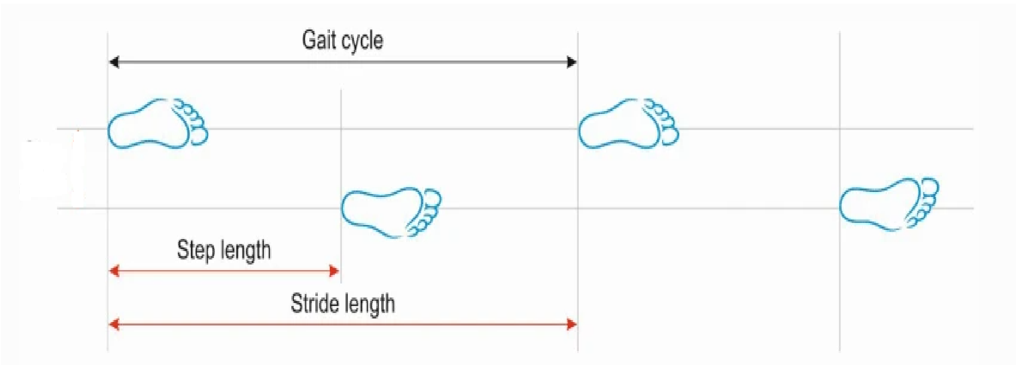


Figure 2.2: Gait cycle terminology[13]

Gait parameters, both spatial and temporal parameters: stride time, stride length, step length, cadence, speed are defined below. All the parameters are considered when the person is walking in a straight path.

Stride Time: Also called as cycle time, is the time taken by the subject to complete a gait cycle.

Stride Length: Stride length as shown in figure 2.2, is the distance between one Heel strike to the next Heel strike of the same leg. This would be the distance traveled by the subject in one gait Cycle.

Step Length: Step length as shown in figure 2.2, is the distance between one Heel strike to the next Heel strike of the alternative leg. Normally step length is half of the stride length[15].

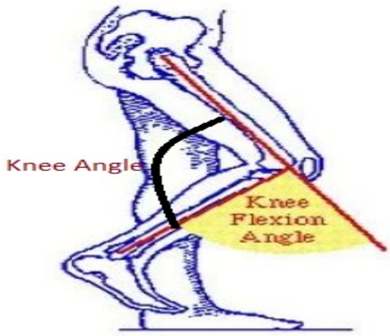
Step Time: The time elapsed between one Heel strike to the next Heel strike of the alternative leg. This would be time taken by the subject to travel the step length.

Cadence: Number of steps per unit time, normally expressed in steps per minute. The cadence of an average person is 110-115 steps/min[15].

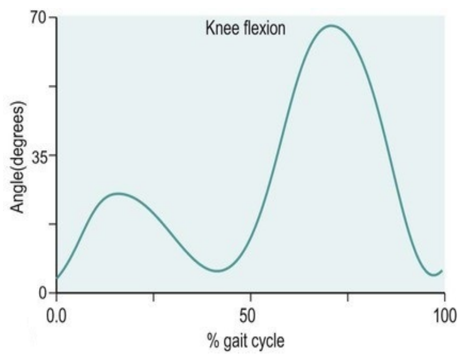
Speed: Distance traveled by a person in unit time. The ratio of the Stride Length and Stride Time.

2.1.3 Knee Flexion Angle

The angle formed by the line connecting hip and knee, and the line connecting knee and ankle is called knee angle. Knee flexion angle is the angle formed by the extension the line connecting hip and knee, and the line connecting knee and ankle, as shown in the figure 2.3(a). It is equal to 180 degrees minus knee angle. The standard knee flexion curve for a gait cycle can be seen in figure 2.3(b). The cycle starts at the Heel strike and ends at the next Heel strike. The curve is the result of plotting the change in the knee flexion angle over time. It can be observed that, at the start of the gait cycle and at the end of the gait cycle we have local minima. This is the reason we took knee flexion angle as reference for calculating the parameters instead of knee angle directly. Kinect is not accurate in estimating the pose of lower extremities like heel and toe joints[16]. This is the key reason why we use the knee joint instead of heel to determine the Heel strike. The lower minima at the beginning and start of the gait cycles represent the Heel strikes when the subject is walking.



(a) Knee and knee flexion angles[15].

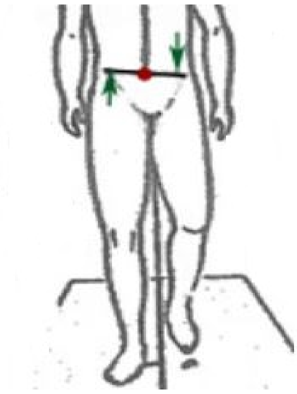


(b) Knee flexion angle over a gait cycle.[17]

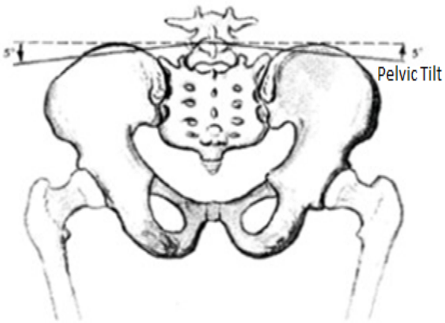
Figure 2.3: Introduction to knee angle

2.1.4 Pelvic Tilt

The orientation of pelvis with respect to the thigh bone and rest of the body is called pelvic tilt. It is shown closely in figure 2.4(b). Pelvic Tilt can be measured by calculating the angle between the line joining neck, hip-center and the line joining hip-center and thigh bone. The pelvic tilt is measured when the subject is walking as shown in 2.4(a) and plotted during a gait cycle and can be analyzed further for medical diagnosis.



(a) Pelvic tilt while walking[15]



(b) Pelvic tilt-close look[15]

Figure 2.4: Pelvic Tilt

2.1.5 Foot Angle

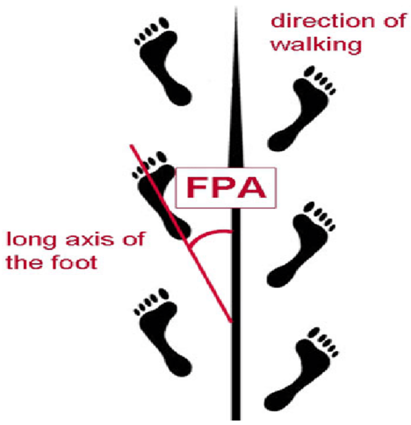


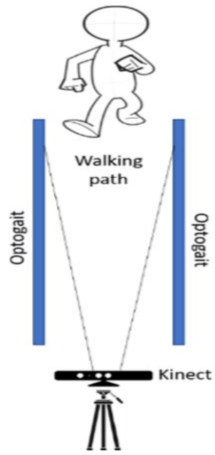
Figure 2.5: Foot Progression Angle(FPA)[18]

The Foot progression angle or simply Foot angle, is another important gait parameter. It is the angle between the line connecting heel, toe, and direction of the progression. The Foot angle is normally measured by wearable sensors. While walking if the feet turn outward, this is called as out-toe and is a common condition. If the feet turn inward it is called in-toe, which is an abnormal gait condition. In figure 2.5, the feet are outward, so it is referred to as out-toe. Foot angle should be calculated when heel and toe, both are on the ground.

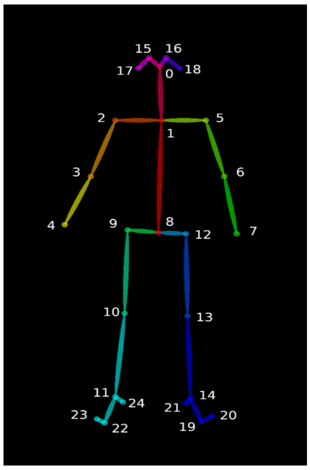
2.2 Data Set

2.2.1 Data Acquisition

Data acquisition is an important aspect in the estimation of gait parameters. Initially, a person starts walking between the railings of Optogait and approaches Kinect, then turns back and walks to the starting point. Optogait is a state-of-the-art system of analysis that can analyze gait precisely. Kinect is composed of three sensors: an RGB color VGA video camera, a depth sensor(includes IR Projector and IR camera), and an array of microphones. The data captured from the RGB color VGA video camera and depth sensor of all individuals are saved for estimating 3D pose. Gait parameters are estimated based on the 3D pose data and can be evaluated by comparing with the results from Optogait[3].



(a) Data acquistion[15]



(b) Pose output format[19]

Figure 2.6: Data acquistion and pose output format

2.2.2 3D Pose Estimation

3D pose estimation involves two stages. Initially, the 2D pose is estimated from the RGB data acquired from the Kinect RGB color VGA video camera, using openpose. Openpose uses Convolutional Neural Networks(CNN) to train the 2D labeled data and provide key joints. The identification of key joints may vary depending on the quality of images[3]. 3D point cloud of the extracted 2D human pose is generated using the depth data acquired from the Kinect depth sensor. The 2D pose from Openpose of the image is mapped with the acquired depth data to generate a 3D pose. The estimated 3D pose with selected key joints is used for calculating gait parameters[3].

The overview of the pose output and description of joints can be seen in figure 2.6(b). The 25 key joints are 0.Nose, 1.Neck, 2.Right shoulder, 3. Right Elbow, 4.Right Wrist, 5.Left Shoulder, 6.Left Elbow, 7.Left Wrist, 8.Mid Hip, 9.Right Hip, 10.Right Knee, 11.Right Ankle, 12.Left Hip, 13.Left Knee, 14.left Ankle, 15.Right Eye, 16.Left Eye, 17.Right Ear, 18.Left Ear, 19.Left Big Toe, 20.Left Small Toe, 21.Left Heel, 22.Right Big Toe, 23.Right Small Toe, 24.Right Heel[19].

2.2.3 Gait Parameters Extraction

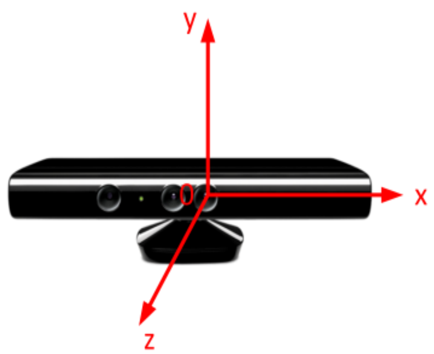


Figure 2.7: Cartesian coordinate system centered at the Kinect[20]

Gait parameters are calculated using the gait cycle plotted by knee flexion angle versus time or frame number. Knee flexion angle is calculated from the vectors formed by hip, knee and knee, ankle joints. The vectors are calculated by the 3D coordinates of these joints which are the result of 3D pose estimation. The x, z coordinates give the horizontal, vertical distance from the Kinect as shown in the figure 2.7. The y-coordinate gives height or vertical distance of a joint from the floor. Theoretically, this means if y-coordinate of the heel is zero or minimum then it is touching the ground. But this depends on the accuracy of Kinect estimating the joints coordinates.

During the time from the subject starts walking till he/she reaches the same position after approaching the Kinect, around 300-400 RGB and depth images are captured. From each pair of RGB and depth images, 2D and 3D pose are estimated. Each frame has 2D and 3D coordinates of 25 joints, so total will be 25*5, 125 values. In the following sections, various ways of gait estimation and how we have estimated the parameters is discussed.

3 Related Work

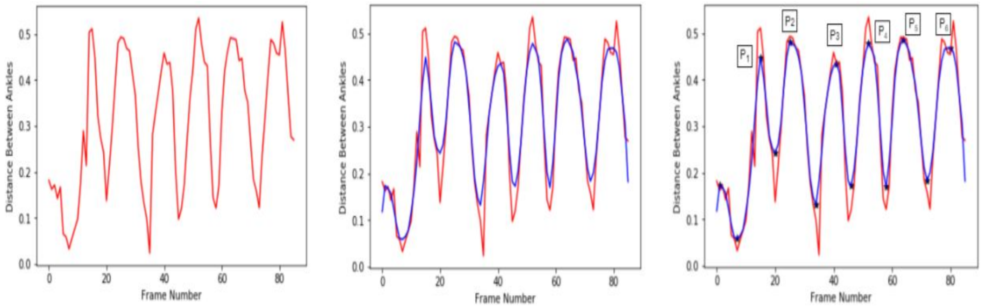
Several techniques are proposed for analyzing and understanding the human gait patterns. They can be classified into wearable and non-wearable technology based on whether the devices are physically attached to the subject or not. Marker-based systems normally use IR cameras and markers are placed on the subject. These systems are good at accuracy but are very expensive and impractical to move. Markers should be placed correctly on the subject's body before each capture. So, these systems are suitable for only laboratories and clinics[21].

Insole pressure sensors can also be used for measuring gait properties. Sensors should be placed correctly and must take gravity, noisy and signal drift into consideration. Wearable sensors are intrusive in the daily routine of the subject and require maintenance in the form of batteries charging and sanitary treatment. Therefore non-wearable technology such as vision-based techniques are focused in the scope of this research. Vision-based techniques use cameras and depth sensors, to directly estimate the body joint positions. In this section various methods used for calculating gait parameters are discussed, related to Kinect.

3.1 Distance Between Ankles

Distance between the left and right ankles is calculated using Euclidean distance for determining a gait cycle. The distance between two ankles is maximum at the time of Heel strike. Ankle distance is calculated for all frames captured by Kinect and plotted versus frame numbers to get multiple gait cycles. The plotted curves are smoothened by moving average filter and secondly a median filter to remove the noise. Once the plots are smoothened, the start and end of each cycle is identified by calculating the local maxima. In figure 3.1(c) P1, P2, P3 P4, P5, P6 are the local maxima. Four gait cycles are extracted from the plot: P1 to P3, P2 to P4, P3 to P5, P4 to P6. If x_1, y_1, z_1 are the coordinates of the left ankle and x_2, y_2, z_2 are coordinates of the right ankle then the Euclidean distance is given by equation 3.1[22].

$$Distance(d) = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{3.1}$$



(a) Distance vector[22] (b) Smoothened Plot[22] (c) Identified local maxima[22]

Figure 3.1: Gait cycle through ankle distance.

3.2 Knee Angle

Knee joint angle is determined by considering the neighboring joints such as hip, ankle in the Cartesian coordinate system. With the Kinect being at the origin of the 3D space, the hip, ankle, and the knee are defined with three vectors as shown in the figure 3.2.

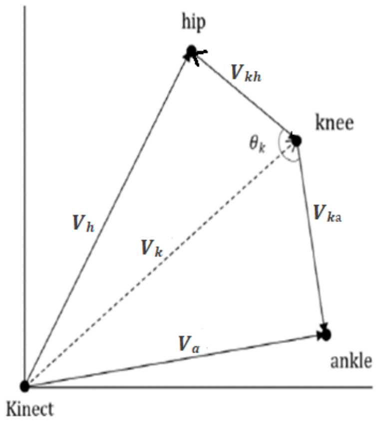


Figure 3.2: Determination of the knee angle[16]

$$\mathbf{V_{kh}} = \mathbf{V_h} - \mathbf{V_k} \tag{3.2}$$

$$\mathbf{V_{ka}} = \mathbf{V_a} - \mathbf{V_k} \tag{3.3}$$

$$\mathbf{U_{kh}} = \frac{(a_1x + b_1y + c_1z)}{\sqrt{a_1^2 + b_1^2 + c_1^2}} \tag{3.4}$$

$$\mathbf{U_{ka}} = \frac{(a_2x + b_2y + c_2z)}{\sqrt{a_2^2 + b_2^2 + c_2^2}} \tag{3.5}$$

$$\theta = cos^{-1}(\mathbf{U_{kh}}.\mathbf{U_{ka}}) \tag{3.6}$$

$\mathbf{V_{kh}}$ is the 3D vector connecting the hip to the knee joint and $\mathbf{V_{ka}}$ is the 3-D vector connecting the knee to ankle. $\mathbf{U_{kh}}$ and $\mathbf{U_{ka}}$ are the unit vectors of $\mathbf{V_{kh}}$ and $\mathbf{V_{ka}}$ respectively[16].

The Foot-off event is considered to have happened when the knee angle of one foot is decreased less than a threshold. This is acquired experimentally throughout some initial experiments. The method using threshold showed 86% accuracy to detect foot-off and foot contact phases[16].

The basic idea of the above mentioned method is extended widely and implemented to calculate gait parameters. This approach is successfully applied for the acquired dataset to calculate the gait parameters and joint angles. This approach is chosen because we can calculate knee angles and pelvic tilt for all frames. Frames where heel-strike and toe-off events occur can be identified and knee angle, pelvic tilt corresponding to these frames can be helpful in machine learning for classification. Moreover comprehensive gait information is possible through this approach unlike that of in the Predictive model where only few parameters of interest can be calculated.

3.3 Predictive Model

Intially, skeleton data is converted into a large set of features consisting of joints' position in each of the frames, the difference in position between consecutive frames(velocity), and the diffeence of the differences(acceleration). The same set of features is computed also for the center of mass, which is the center of the hip joints. Both the set of features constitutes feature vector. Multiple Additive Regression Trees algorithm is used to predict the stride duration and other values of interest from the feature vector[21].

To build and evaluate the prediction model Kinect skeleton recordings of walking subjects with time synchronised readings from in-shoe pressure sensors and a gyroscope attached to the wrist via straps. The accuracy of the method is evaluated by comparing extracted parameters from the skeleton to the reference values from the pressure sensor. Stride duration is calculated with an error of only 35–71ms and correlation coefficient between the prediction and the true value for arm angular velocity is 0.9[21].

4 Implementation

RGB and depth data is already captured and 3d pose is estimated for around 300 people. The data associated with each person is named as Proband-xx, where 'xx' is the internal id given for identification. With each person the experiment is conducted five times, so for each proband, we have five experiments. This project aims to extract gait parameters for all the probands through joint angles, mainly based on the knee flexion angle. The process is automated so that for any number of people or experiments, parameters are calculated by running the program, just once, without any manual tasks.

4.1 Knee Flexion Angle

4.1.1 Data Pre-Processing

The estimated 3D pose is the input data in its raw form and the accuracy of parameters is based on the accuracy of the 3D pose data and pre-processing. Pre-processing involves dealing with missing values and removing impossible values, selecting only the data of joints that are required. The latter two are important in improving performance by reducing the computational effort. For each experiment, we have 300-400 frames extracted from RGB and depth images. Each frame represents an RGB and a depth image, and contains 2D and 3D pose coordinates of 25 joints of the human skeleton. So, each frame has 125 values and also the frame number in the first position, making it 126 values for each frame. Each experiment has m rows and 126 columns in an excel sheet. m is the number of frames and changes for each experiment.

At first excel file is imported into a Matlab variable using 'xlsread' function. The matrix variable will have a size of m*126. The frame number is important to recognize a frame and map with the corresponding RGB image. Initially, the frames are random in sequence and are sorted by frame numbers in ascending order. For knee flexion angle we need only hip, knee, and ankle joints coordinates and a frame number. So we, take only these 16 values for each frame to reduce the unnecessary computations and execution time. The resultant size of the variable would be m*16. To fill the missing values, we calculate the average of the previous value and the next value in a column. If Kinect could not capture a coordinate, this is given as 56 in the 3D pose. So we replace all the 56 values with the zeros. After this, all the rows are removed even if one column is zero. This is done based on trial and error to get smooth gait cycles.

At the time of data acquisition, once the user reaches the Kinect, the subject takes a U-turn to go back to the initial point. During the U-turn only a portion of the subject's body is captured. These rows(frames) are already are removed, based on the presence of zeros using a predefined Matlab function.

Apart from removing the rows with zeros, the rows of the RGB data where the subject is too nearby to the Kinect are removed. To do this we find the difference of each frame number with index i and next frame number whose index is i+10. If the difference is greater than 15 then we remove the rows by replacing them with Nan. The difference would be greater than 15 because we removed the rows based on the presence of zeros. When the subject is too nearby, as shown in the figure 4.1, the coordinates of many joints are not captured, so they are zeros. The frame number of i index is considered to be the start of the U-turn and the frame number of (i+10)th index is the end of the U-turn. This approach is successful in recognition of when the U-turn starts and ends. In the figure, you can see RGB pictures captured during the U-turn. There will be around 20-35 frames captured during the U-turn, which will be identified and removed.

The difference of the ankle's z-coordinate of each frame is calculated with the next frame and if it is more than a threshold, then the coordinate made Nan. This specific coordinate is filtered to remove the noise. Normally, as the person approaches Kinect, the z-coordinate(vertical distance from Kinect) should decrease gradually.

(a) Full Capture while approach (b) Partial Capture while approach (c) Partial Capture while leaving

Figure 4.1: RGB images when the subject is far and too nearby to Kinect

4.1.2 Knee Flexion Angle Calculation

The knee angle is calculated for each frame in the experiment using the preprocessed data. At first, vectors are formed between the hip and knee, knee and ankle as shown in the figure 4.2. Each vector is formed by calculating the difference between coordinates. If x_1, y_1, z_1 are the coordinates of the hip, x_2, y_2, z_2 are the coordinates of the knee, x_3, y_3, z_3 are the coordinates of ankle then the vectors formed are $\mathbf{V_{kh}}$ and $\mathbf{V_{ka}}$.

$$\mathbf{V_{kh}} = \mathbf{V_h} - \mathbf{V_k} \tag{4.1}$$

$$\mathbf{V_{kh}} = (x_1 - x_2)x + (y_1 - y_2)y + (z_1 - z_2)z \tag{4.2}$$

$$\mathbf{V_{ka}} = \mathbf{V_a} - \mathbf{V_k} \tag{4.3}$$

$$\mathbf{V_{ka}} = (x_3 - x_2)x + (y_3 - y_2)y + (z_3 - z_2)z \tag{4.4}$$

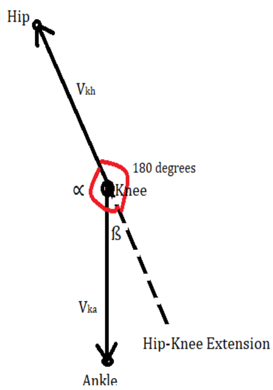


Figure 4.2: Knee-hip and knee-ankle vectors

In figure 4.2, α and β are the knee and knee flexion angles. In the figure it can be observed that α and β are supplementary , the sum of α and β is 180°.

$$\alpha + \beta = 180° \tag{4.5}$$

$$\beta = 180° - \alpha \tag{4.6}$$

At first, the dot product of two vectors is calculated. Then the magnitude of the vectors are calculated. Using the dot product and magnitudes, the knee angle, α is calculated. Equation 4.7 gives the dot product of the two vectors.

$$\mathbf{V_{kh}}.\mathbf{V_{ka}} = (x_1 - x_2).(x_3 - x_2) + (y_1 - y_2).(y_3 - y_2) + (z_1 - z_2).(z_3 - z_2) \tag{4.7}$$

x_1, x_2 are the x-coordinates of hip and knee respectively for a given frame. In Matlab, the difference of these x-coordinates for all frames is calculated at once by simple subtraction of respective matrix columns. In the same way all the computations are calculated at column level. At the end, angles are also calculated for all frames at once.

$$|\mathbf{V_{kh}}| = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \tag{4.8}$$

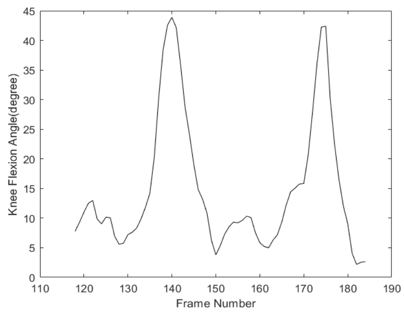
$$|\mathbf{V_{ka}}| = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2 + (z_3 - z_2)^2} \tag{4.9}$$

$$\cos\alpha = \frac{\mathbf{V_{kh}}.\mathbf{V_{ka}}}{|\mathbf{V_{kh}}| * |\mathbf{V_{ka}}|} \tag{4.10}$$

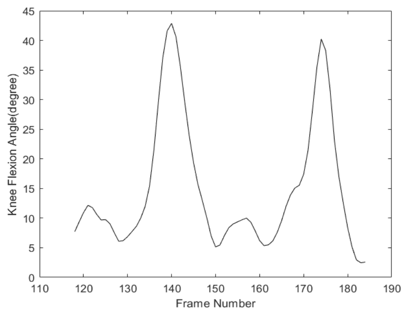
$$\alpha = cos^{-1}(\frac{\mathbf{V_{kh}}.\mathbf{V_{ka}}}{|\mathbf{V_{kh}}| * |\mathbf{V_{ka}}|}) \tag{4.11}$$

Knee flexion angle, β is calculated by equation 4.6. Knee flexion angles of all frames are plotted against frame numbers to get gait cycles.

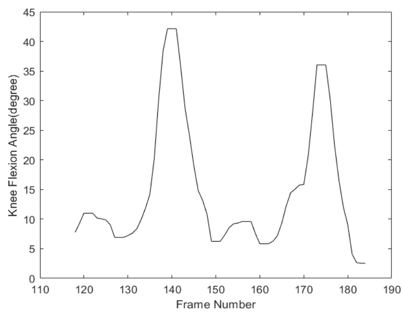
4.1.3 Smoothening



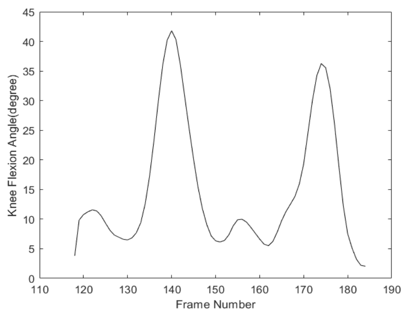
(a) Smooth filter.



(b) Smooth + Movmean(window-3) filters



(c) Smooth + Movmedian(window-5) filters



(d) Smooth + Sgolay(window-11) filters

Figure 4.3: Smoothening with different filters.

Knee flexion angle plot must be smoothened to remove the noise. Smoothening must be done carefully because over smoothening can remove the crucial peaks(maxima). More importantly, smoothening technique should be applicable for all the probands. At first, angles which are more than 55 are suppressed, to remove the improbable knee flexion angles. Then we use ‘smooth’ function in Matlab and the result can be seen in figure 4.3(a). To further smoothen it, we use Movmean, Movmedian, Sgolay filters along with Smooth function. Smoothening is achieved best with the combination of Smooth and Sgolay filter with a window of 11, as shown in the figure 4.3(d). Different windows are used based on trial and error, and best suiting window is selected. To avoid false maxima and minima, gait cycles should be very smooth. Also, identification of the start and end of the gait cycle depends on the smoothness of the curve.

4.1.4 Gait Cycle Identification

In figure 4.3(d) there are two gait cycles. Gait cycles with knee flexion angle of every person have a standard shape. This is shown in figure 2.3(b). One way to find out the start and end is by using the findsignal function in Matlab, which looks for the exact shape of a signal in a plot. This can be seen in figure 4.4. But the findsignal looks for the exact shape in the plot, which makes actual gait cycles not getting identified, in all experiments. So, local maxima and minima are calculated to identify the start and end of the gait cycles. Each gait cycle has a fixed sequence of minima and maxima. Using these minima and maxima, start and end of the gait cycles are identified. For some experiments, even after smoothening there are minima and maxima which are very nearby as shown in figure 4.5(b). These false minima and maxima are ignored by using a threshold. This threshold is selected on the basis of trial and error, and based on the fact that real peaks cannot be very nearby.

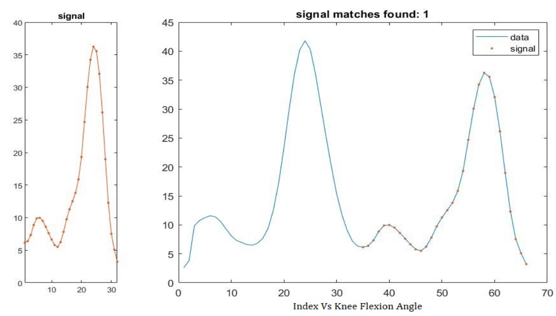
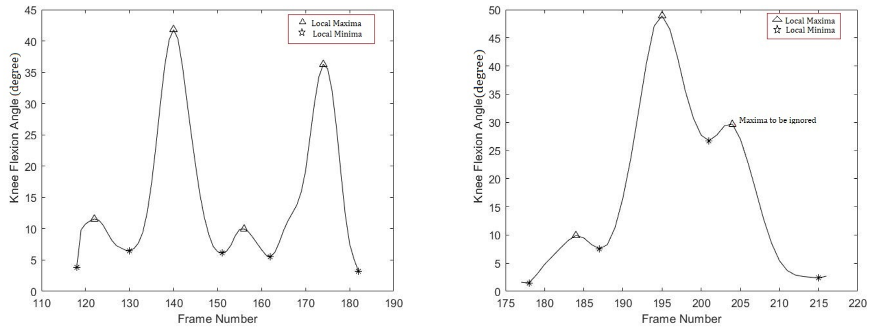


Figure 4.4: Identifying gait cycles using Findsignal



(a) Local Maxima and minima (b) Maxima which are too nearby

Figure 4.5: Identifying maxima and minima

4.2 Gait Parameters Calculation

Once the frame numbers are identified for the start and end of the gait cycle, gait parameters are calculated. Kinect captures 25 frames per second, so the time interval between each frame is 1/25(0.04sec).

4.2.1 Stride Time

Stride time or Cycle time is the time taken by the subject to complete a gait cycle. If f_1 and f_2 are the frame numbers at the start and end of the gait cycle respectively, then Stride time is given by equation 4.12.

$$Stride\_Time = (f_2 - f_1) * Time\_Interval \tag{4.12}$$

4.2.2 Stride Length

Stride length is the distance traveled by the subject in one gait cycle. For this, the displacement of the ankle from f_1 to f_2 is considered. Displacement of the ankle is calculated by the Euclidean distance. If x_1,y_1,z_1 are the coordinates of the ankle in frame f_1 and x_2,y_2,z_2 are the coordinates of ankle(same leg) in frame f_2, then the Euclidian distance is given by equation 4.13.

$$Stride\_Length = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{4.13}$$

4.2.3 Step Time

Step time is the time elapsed between the Heel strike of one leg to the Heel strike of the alternate leg. Step time is considered to be half of the stride time as there will be two steps for each stride.

$$Step\_Time = \frac{Stride\_Time}{2} \tag{4.14}$$

4.2.4 Step Length

Step length is the distance between one Heel strike to the next Heel strike of the alternative leg. Step length is considered to be half of the stride length.

$$Step\_Length = \frac{Stride\_Length}{2} \tag{4.15}$$

4.2.5 Speed

Distance traveled by the subject in unit time. This is calculated using stride length and stride time.

$$Speed = \frac{Stride\_Length}{Stride\_Time} \tag{4.16}$$

4.2.6 Cadence

The number of steps per unit time is called cadence. Since each stride has two steps, cadence is given by equation 4.17.

$$Cadence = \frac{2}{Stride\_Time} \tag{4.17}$$

4.3 Pelvic Tilt

4.3.1 Pelvic Tilt Calculation

The data pre-processing is the same as that of the knee flexion angle. Coordinates of neck, mid-hip, hip(right/left) are selected for pre-processing, and angle is calculated by forming the vectors between mid-hip, neck and mid-hip, hip as shown in the figure 4.6. We assume that ideally, the angle between these two vectors is 90°, and any deviation is considered to be pelvic tilt. During walk, hip moves back and forth with respect to mid-hip. So pelvic tilt can be both positive and negative as the person walks. Pelvic tilt can be calculated for the right hip or left hip in the same way. If x_1, y_1, z_1 are the coordinates of neck(n), x_2, y_2, z_2 are the coordinates of mid-hip(m), x_3, y_3, z_3 are the coordinates of hip(h) then the vectors formed are $\mathbf{V_{mn}}$ and $\mathbf{V_{mh}}$.

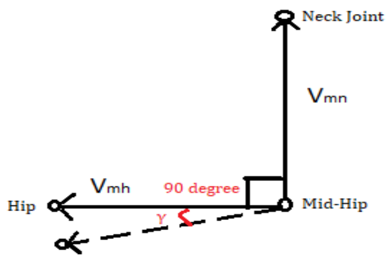


Figure 4.6: Pelvic tilt

$$\mathbf{V_{mn}} = \mathbf{V_n} - \mathbf{V_m} \tag{4.18}$$

$$\mathbf{V_{mn}} = (x_1 - x_2)x + (y_1 - y_2)y + (z_1 - z_2)z \tag{4.19}$$

$$\mathbf{V_{mh}} = \mathbf{V_h} - \mathbf{V_m} \tag{4.20}$$

$$\mathbf{V_{mh}} = (x_3 - x_2)x + (y_3 - y_2)y + (z_3 - z_2)z \tag{4.21}$$

At first the dot product and magnitude of the two vectors are calculated. Using the dot product and magnitudes, the angle between the two vectors, ϑ is calculated.

$$\mathbf{V_{mn}}.\mathbf{V_{mh}} = (x_1 - x_2).(x_3 - x_2) + (y_1 - y_2).(y_3 - y_2) + (z_1 - z_2).(z_3 - z_2) \tag{4.22}$$

$$|\mathbf{V_{mn}}| = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \tag{4.23}$$

$$|\mathbf{V_{mh}}| = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2 + (z_3 - z_2)^2} \tag{4.24}$$

$$\cos\theta = \frac{\mathbf{V_{mn}}.\mathbf{V_{mh}}}{|\mathbf{V_{mn}}| * |\mathbf{V_{mh}}|} \tag{4.25}$$

$$\theta = cos^{-1} \frac{\mathbf{V_{mn}}.\mathbf{V_{mh}}}{|\mathbf{V_{mn}}| * |\mathbf{V_{mh}}|} \tag{4.26}$$

From figure 4.6 we can observe that ϑ is the sum of pelvic tilt, γ and $90°$. pelvic tilt γ is ϑ minus $90°$.

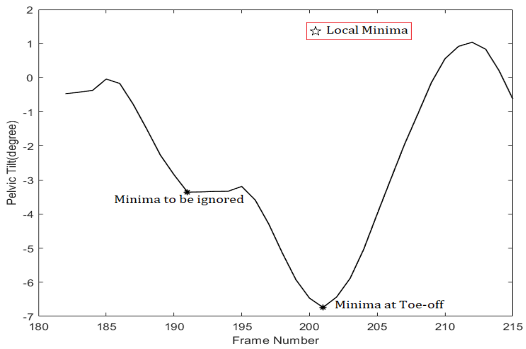
$$\theta = \gamma + 90° \tag{4.27}$$

$$\gamma = \theta - 90° \tag{4.28}$$

4.3.2 Stance Phase and Swing Phase

During a gait cycle, the transition from the stance phase to swing phase happens at Toe-off when the subject's toe leaves the ground as shown in the figure 4.7(a). The stance phase and swing phases cover 62% and 38% of the gait cycle approximately. However, these percentages change for each person. To know the phases exactly, we need to detect the time of Toe-off precisely. It is observed from RGB images that at Toe-off the subject's pelvic tilt plot has a local minimum in the Pelvic tilt vs Frame number plot as shown in the figure 4.7(b). From the knee flexion angle plot we know the frame numbers at which the gait cycle starts and ends. We look for local minima from 55% to 75% (percentages based on trial and error) of the gait cycle, to avoid false minima at the end or start of the cycle. So, we know exactly the frame at which Toe-off happens. Using this frame number, we can calculate the phases without assuming any thresholds or approximate values.

(a) Toe-off of right leg from RGB image(frame 200)



(b) Pelvic tilt

Figure 4.7: Detecting Toe-off using pelvic tilt

4.4 Foot Angle

Foot angle can be calculated when both heel and toe, both are present on the floor. For this the frame in which both heel and toe are on the ground, should be identified(previously we detected only Heel strike). The y-coordinate of a joint gives the vertical distance from the ground. So when heel and toe are on the ground the y-coordinate should be equal and minimum(if not zero). The very fact that either ankle distance or knee flexion angle is used to calculate the gait parameters is because the pose estimation of heel and toe coordinates are not accurate from Kinect. This means we cannot precisely detect at what time(frame) the heel and toe are on the floor. Literature suggests that

Kinect lacks the accuracy in detecting the lower extremities like toe and heel, although the accuracy is good for detecting upper body part movements[16].

It is further observed that in some experiments the z-coordinate of the toe and heel does not change at all for each frame, which means the person is not moving at all, but this is not the case. Also, sometimes the z-coordinate of the heel and toe are equal which means the size of the foot is zero. So, for the lower extreme joints-heel and toe, we do not have accurate coordinates to detect the floor contact as well formation of the vectors.

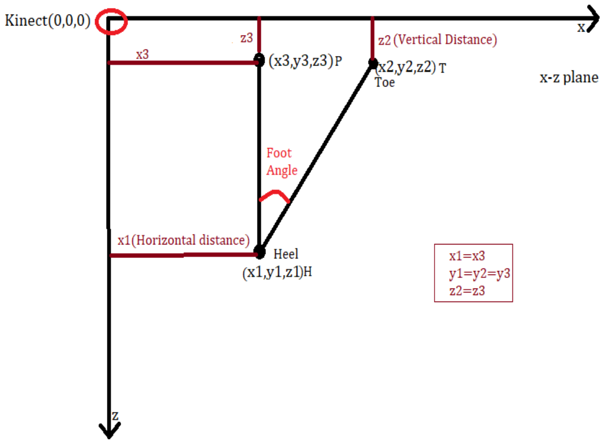


Figure 4.8: Calculation of foot angle

If we can detect the heel and toe joints correctly, we can find the foot angle by forming the vectors between heel and toe, progression line as shown in the figure 4.8. There is no progression line physically, so we assume a point 'P' which is at the same distance as heel horizontally and at the same distance as toe vertically. The point 'P', heel, and toe lies on the same plane, as all of them on the floor. So, the y coordinate of all the three points is equal. We can form vectors $\mathbf{V_{HT}}$ and $\mathbf{V_{HP}}$ and calculate the angle in the same way as knee flexion angle and pelvic tilt. But the problem would be the detection of the heel and toe contacting the ground precisely which is not possible due to the lack of accuracy of data for these two joints. There is scope for future research to improve the detection of lower extreme joints to calculate the foot angle and can be verified by the foot angle measured during data acquisition. The checkpoint would be detecting the heel and toe contact to ground precisely with the respective coordinates.

5 Results and Evaluation

5.1 Knee and Knee Flexion Angles

Initially, 2D pose data is used to calculate the knee flexion angle, but gait cycles are not obtained. With the 3D pose data, gait cycles are obtained for every experiment. Gait cycles are obtained particularly when the subject is approaching the Kinect and before the person is taking the U-turn. When the person is leaving the Kinect, throughout the journey, there are no gait cycles observed. This means pose estimation is accurate when the person is approaching at a particular distance from Kinect.

For every experiment knee angles, knee flexion angles are calculated for all frames and are plotted against frame numbers as shown in the figures 5.1 and 5.2(b). This is done for both the left knee and right knee. For each knee, gait cycles are observed when the subject is approaching the Kinect and before taking the U-turn. Gait parameters are calculated for both the gait cycles and the average is calculated. In some experiments, we get only one gait cycle because of the accuracy of 3D pose data. In the same way, gait parameters are calculated for both left and right knee calculated and final parameters are the average of these two sets of parameters. The results of the proposed approach are shown in Table 5.1.

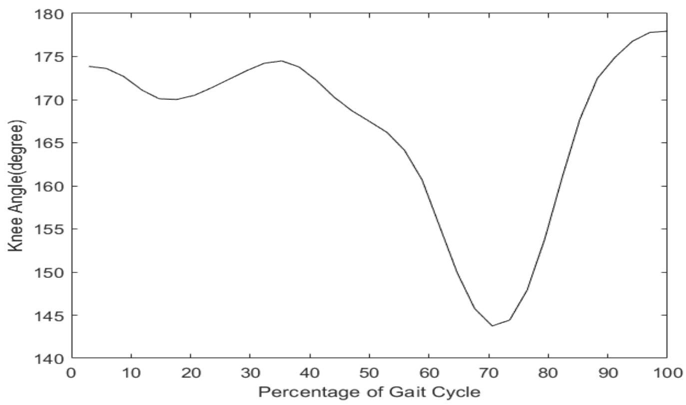
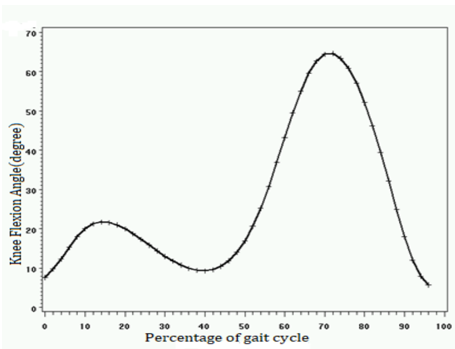


Figure 5.1: Knee angle over a gait cycle

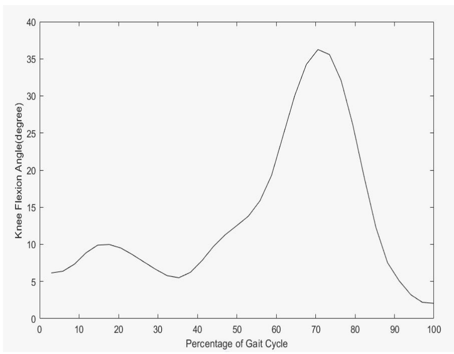
Table 5.1: Calculated gait parameters comparison with Optogait

Parameters						
Method	Stride Time (sec)	Stride length (cm)	Step Time (sec)	Step Length (cm)	Speed (m/sec)	Cadence (steps /min)
Optogait	1.04	124.3	0.52	62.15	1.21	97.2
Proposed approach	1.12	126.63	0.56	63.31	1.13	106.2

Knee flexion angles and pelvic tilt are calculated for both left and right sides for all experiments by automating the process completely. As we have identified the start and end of the gait cycle, we know the knee angles, pelvic tilt at Heel strike, and toe-off of a person. This data is used for training purposes in machine learning to diagnose any neurological diseases. Gait cycle obtained by calculating knee flexion angles is shown in figure 5.2(b) and compared with the gait cycles referred from the literature [23].



(a) Standard Gait Cycle[23].



(b) Obtained Gait Cycle.

Figure 5.2: Standard gait cycle VS Obtained gait cycle

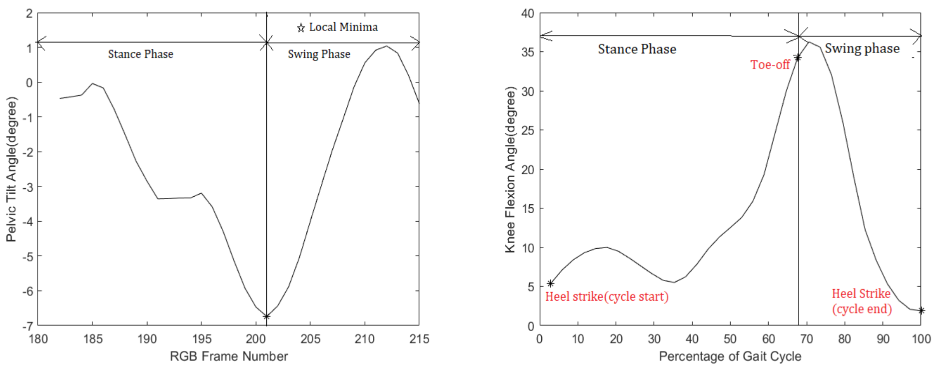
The calculated gait parameters are compared with the parameters from Optogait. It is a state-of-the-art system based on optical detection[24]. The parameters from the optogait are considered as ground truth. The percentage of accuracy is calculated by equation 5.1 and the average results for 50 people are listed in table 5.2.

$$accuracy = (1 - \frac{|Estimated\_value - Optogait\_value|}{Optogait\_value}) * 100 \tag{5.1}$$

Table 5.2: Accuracy of gait parameters estimated

Parameters Accuracy					
Stride Time (%)	Stride length (%)	Step Time (%)	Step Length (%)	Speed (%)	Cadence (%)
81.41	80.42	81.41	80.42	80.5	80.87

5.2 Pelvic Tilt



(a) Pelvic tilt over a gait cycle

(b) Identifying Toe-off using pelvic tilt

Figure 5.3: Stance and Swing Phases

From knee flexion angles plot, start(Heel strike) and end(next Heel strike) of the gait cycles are identified. To calculate the stance and swing phases the frame at which the Toe-off event happens needs to be identified. The pelvic tilt is used to identify the Toe-off based on the local minima as shown in figures 5.3(a) and 5.3(b).

The stance phase and swing phase are calculated without using any threshold angle by identifying the time(frame) at which Toe-off is happening. The results are verified by observing the RGB images which is the ground truth. The accuracy is calculated by comparing the frame number we detected with the RGB frame number which shows Toe-off. The accuracy of stance phase and swing phases are calculated by comparing the frame numbers detected by the proposed approach with the actual frame numbers from RGB images which are actually the ground truth. The percentage of the accuracy is calculated by equation 5.2 and the results are shown in table 5.3. The accuracy is calculated for ten different people and the average is 90.1%

$$accuracy = (1 - \frac{|Frame\_detected - RGB\_frame|}{Total\_frames\_in\_gait\_cycle}) * 100 \qquad (5.2)$$

Table 5.3: Comparison of events detected VS ground truth

Frame Number at Toe-off event			
Experiment	Ground truth from RGB images	Proposed approach	Accuracy
Proband_101_CB1	201	201	100
Proband_101_CB3	145	143	93.9
Proband_101_CB7	115	115	100
Proband_101_RG1	116	115	97

6 Conclusion

Human gait is an important metric related to a person's health and well being. Detecting abnormality in gait is important for the diagnosis of neurological diseases like dementia. Kinect is a cost-effective sensor and can be easily installed at clinics and homes. The advantages and technology of Kinect can be taken leverage of, to detect Dementia in early stages by analysing the gait over the long-term.

Gait analysis has three main stages: Data acquisition, 3D pose estimation, Parameters extraction. This project mainly focuses on Parameters extraction and achieved an average accuracy of more than 80%, calculated for 50 different people. The accuracy of the parameters extracted can be increased by obtaining more number of gait cycles. This can be achieved by improving the 3D pose data. More the 3D pose data is accurate, the more the number of gait cycles and more would be the accuracy in gait parameters and reliable would be the medical diagnosis. The knee flexion angle, pelvic tilt, and gait parameters can be used combinedly in machine learning classification to identify a person if he is moderately or seriously affected by dementia.

The future scope of this research would be to use the gait parameters and joint angles to diagnose a person for neurological diseases especially elderly people, with the help of machine learning techniques. Also, gait can contribute to Biometrics through identity verification as it does depend upon the appearance of the person. Gait information: joint angles, gait parameters, length of the limbs can be used combinedly to identify a person. In the future the proposed approaches can be applied to the data from other depth sensors like Intel Real sense cameras with different ranges and the results can be validated to check if we can improve the accuracy of the gait parameters.

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